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Technical Report

SENSITIVITY ANALYSIS OF REFLECTION ERRORS IN INFRARED IMAGE SIMULATION

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- 4) A weighted average error figure was derived and applied to the results of histogramming emissivities for the simulated tank.
- 5) It was determined that in some cases, error could be as high as 35% on an absolute scale. However, most of the errors calculated in section 3.0 were found to be less than 10%, which corresponds to about 6°K apparent temperature error for ambient targets.

Average error for a typical target was found to be on the order of 6°K apparent temperature when its IR signature was simulated using FSTC's current method. FSTC personnel must judge whether 6°K apparent temperature error is significant before further action is planned.

EXECUTIVE SUMMARY

The question of how much error is present in a simulated infrared signature if reflections are neglected was studied using a sensitivity analysis approach. The purpose of this study was to determine whether it is necessary to model reflections in the current FSTC method of simulating IR signatures. To gain more insight the following steps were performed:

- 1) A sensitivity analysis approach was chosen for the study,
- 2) An equation isolating the major components of an IR signature was derived,
- 3) The equation was used to determine error present in a simulation when emissivity was estimated to be always 0.95. This was accomplished by using a simulation of a complicated tank applied with actual, measured emissivity that had specular characteristics,
- 4) A weighted average error figure was derived and applied to the results of histogramming emissivities for the simulated tank,
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1.0
WHY A SENSITIVITY ANALYSIS OF IR SIMULATION?

This report is the second in a series addressing the issue of how much error is introduced into IR target simulations by neglecting the effects of reflections from a target's environment. Technical Memo #1 of this contract explored, through a case study analysis, reflections in the IR and the error caused by neglecting them in a simulation. This report explores the same issue through a sensitivity analysis approach.

A rigorous simulation of IR signatures should include not only target self-emission, but reflections from its environment and itself. However, neglecting reflections reduces the cost of software development and data preparation. The question of whether reflections need to be included in an IR simulation is, thus, an important one since it is recognized that target emission is often dominant in the IR wavelengths. Whether or not the additional expense of including reflections is justified is ultimately determined by the required simulation accuracy. An ideal situation would be a simulation that is "accurate enough" for a given purpose and models only target emission, in order to avoid more expensive development and preparation. It is the intent of this report to illustrate the magnitude of error that results from ignoring reflections. The significance of these errors must be judged by FSTC personnel.

Approaches to Modeling Emissivity and Reflections

In general, surfaces can be modeled as either perfectly specular, perfectly diffuse, or somewhat intermediate to these extremes. Diffuse surfaces with high emissivity (>0.95), can be modeled with $\sim 3^\circ\text{K}$ apparent temperature¹ error [3]. Depending on the use of the simulation, this may be adequate or inadequate. FSTC currently assumes that this error is

1. Apparent temperature is the temperature of a perfect emitter whose radiance equals that received from the target.

acceptable and assumes that most modeled materials are diffuse and have an emissivity close to 0.95.

However, for surfaces that are significantly specular, not diffuse as modeled by FSTC, certain viewer/target geometries will result in a large amount of reflections. Neglecting reflections when simulating an image of a specular target at certain viewer/target geometries may result in large and even unacceptable error. The question to be answered is: How often and how large will the error be from neglecting reflections when simulating IR imagery?

A Sensitivity Analysis Applied to IR Image Simulation

In order to achieve a better understanding of the importance of various factors in an IR image, a sensitivity analysis was used. The analysis was performed using the factors known to be important in an IR image. These factors are:

- emissivity
- surface temperature
- reflection component.

Figure 1 depicts the three components of an IR image.

Emissivity is a function of surface material properties, wavelength and viewer/target geometry (if it is a material that has significant specular behavior). Most military type paints exhibit some specularity, i.e., emissivity decreases with decreasing grazing angle as shown in Figure 2. This fact in large part has prompted the present study.

Surface temperature is used to compute the emitted radiance leaving the target. The relationship between temperature, wavelength and emitted radiance is described by Planck's law. FSTC's simulation uses Planck's law to compute emitted radiance.

Reflection component is often characterized by an apparent source temperature and the true emissivity of the target. Thus, a clear night sky is often said to be at an apparent temperature of, say, 240°K, and its

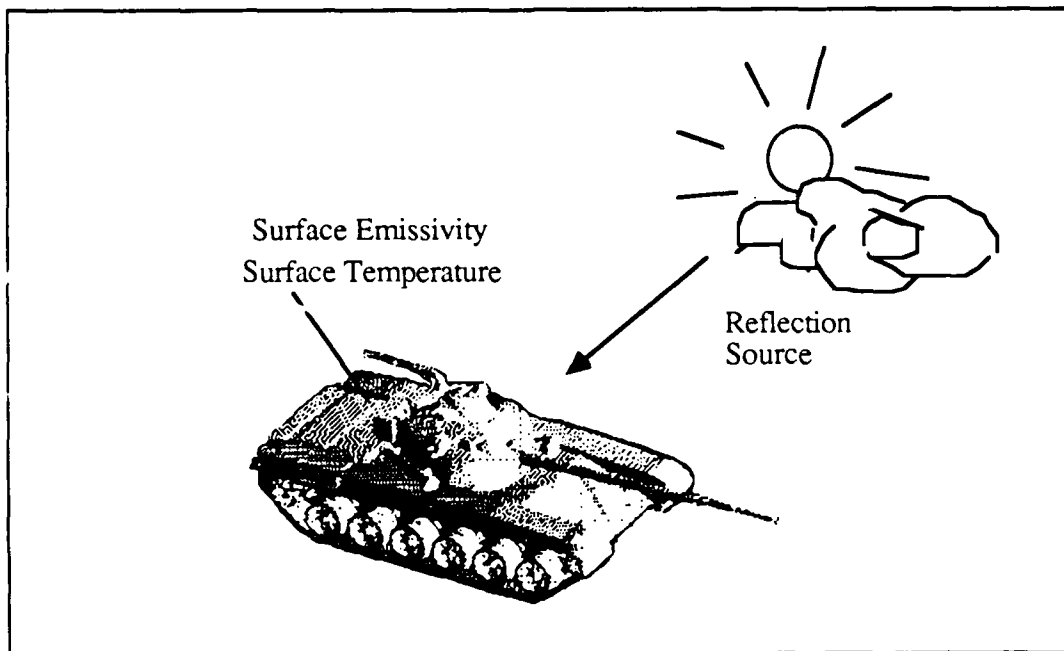


FIGURE 1. THE THREE COMPONENTS OF AN IR SIMULATION STUDIED IN THIS REPORT.

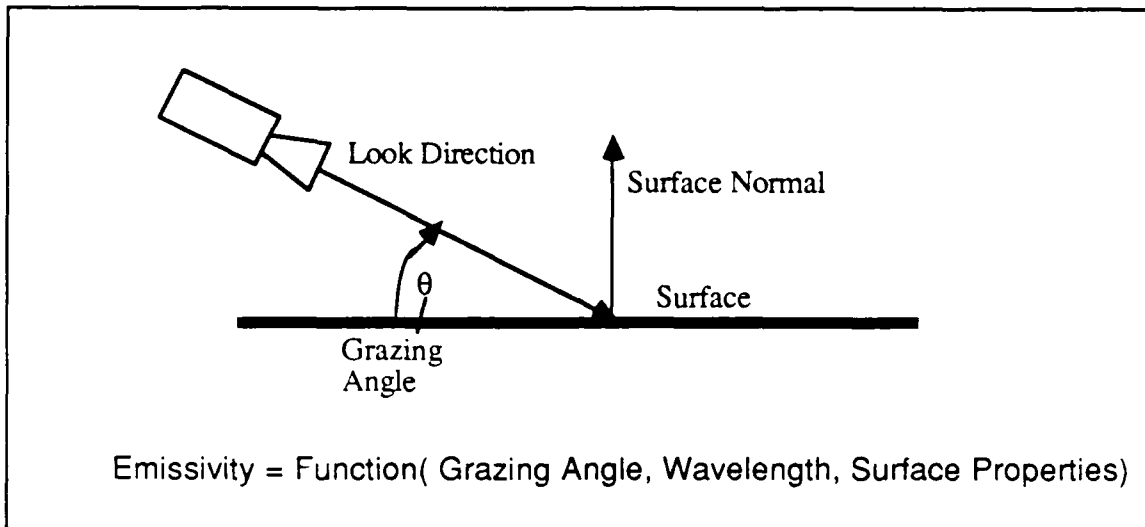


FIGURE 2. FACTORS THAT AFFECT THE VALUE OF EMISSIVITY.

radiance is obtained from Planck's law, similarly to surface temperature. This radiance is then reflected off the target in an amount determined by the latter's emissivity/reflectivity properties. For the predominantly specular target considered in this report, only a single source direction need be considered. In the general case, the reflection component of a target signature includes contributions from an entire hemisphere of source temperatures (cf., equation A-7 in the Appendix).

The purpose of the sensitivity analysis is to determine the magnitudes of error that could be expected in the current simulation method used by FSTC. The current method assumes:

- 1) Uniform emissivity (i.e., independent of view angle), typically 0.95 for 8-14 μm simulations and 0.6 for 3-5 μm simulations.
- 2) Reflections of any sort are an insignificant component of the total signature.

Both of these assumptions are open to question. The current study is intended to illuminate exactly how erroneous, or how accurate, these assumptions can be.

2.0 COMPUTING SENSITIVITY TO ERROR

An equation that relates the error in final radiance given that emissivity, surface temperature, and the reflection term have been incorrectly estimated is:

$$\Delta L = (\hat{\epsilon} - \epsilon) L(T_T) + \hat{\epsilon} \left[\frac{\partial L}{\partial T} \right]_{T_T} \Delta T - (1 - \epsilon) L(T_S) \quad (1)$$

where:

ϵ = true emissivity of the target

= $f(\Delta\lambda, \theta)$,

$\Delta\lambda$ = integrated wavelength band,

θ = grazing angle between viewer and target,

$\hat{\epsilon}$ = estimated emissivity of the target,

$L()$ = Planck operator that computes radiance based on temperature and radiance,

T_S = apparent temperature of source of reflection,

T_T = actual temperature of target,

ΔT = $(\hat{T} - T)$ or difference between estimated temperature and actual value.

The derivation of equation 1 is presented in Appendix A. Equation 1 is used as the basis of the following sensitivity analysis.

Each of the three terms in equation 1 can be interpreted as being the error contribution for each of the three factors in an IR image identified in section 1.0. The error due to incorrectly assigning emissivity is:

$$(\hat{\epsilon} - \epsilon) L(T_T) \quad .$$

The error due to incorrectly assigning surface temperature is:

$$\hat{\epsilon} \left(\frac{\partial L}{\partial T} \right)_{T_T} \Delta T$$

and the error due to reflections is:

$$(1 - \epsilon) L(T_S) \quad .$$

2.1 REDUCING THE RADIANCE EQUATION TO AN ERROR EQUATION

Absolute radiance error in terms of physical units lends little insight into the question of how "big" an error is actually present. One way of introducing relativity is to normalize equation 1 in order to produce a unitless quantity on the left side. The question is, normalize with what quantity? An obvious answer would be to normalize with $L(T_T)$ to produce:

$$\frac{\Delta L}{L(T_T)} = (\hat{\epsilon} - \epsilon) + \frac{\hat{\epsilon}}{L(T_T)} \left(\frac{\partial L}{\partial T} \right)_{T_T} \Delta T - (1 - \epsilon) \frac{L(T_S)}{L(T_T)} \quad (2)$$

where now, $\Delta L/L(T_T) = 1.0$ would be interpreted as 100% error.

2.2 SELECTING FOUR CASES OF REFLECTANCE STRENGTH

Equation 2 is difficult to understand because of the complex manner in which the various terms can interact with one another. One way of reducing this difficulty is to select one or two of the variables in equation 2 to be looked at discretely, that is select a few cases and then vary the other variables continuously. As mentioned earlier, Technical Memo #1 pointed to emissivity as a driving factor in error. Therefore, $L(T_S)/L(T_T)$ will be set at a few discrete values and emissivity and other terms will be varied. This will be used to establish a trend in error calculations as a result of view angle dependent emissivity.

What values of $L(T_S)/L(T_T)$ to choose? Two limiting values, such as $L(T_S)/L(T_T) = 1$ and 0, are useful in order to gain insight into error.

Two other intermediate values will fill out the solution space sufficiently to understand how the error will vary. For ease of discussion, let

$$\frac{L(T_S)}{L(T_T)} = R_r \quad \{\text{Reflectance ratio}\} \quad .$$

When $R_r = 1$, the implication is that the source of reflection $T_S = T_T$, the target temperature. When $R_r = 0$, the implication is that $T_S \ll T_T$, or that the source of reflection is much less than the target. This would be typical of a hot exhaust stack. For the in between values, it's more difficult to relate some actual scenarios to some typical values. If $R_r = 0.5$ is chosen, one situation that can cause this is $T_S = 275$ and $T_T = 320$ (among others). This could be typical of a warm vehicle sitting in an open field during the winter. If $R_r = 0.667$, a situation that could cause this is $T_S = 300$ and $T_T = 320$, which could be typical of a warm vehicle sitting in an urban setting. Other interpretations could be applied. Table 1 summarizes the reflectance ratios chosen.

TABLE 1	
Reflectance ratios, $L(T_S)/L(T_T)$, chosen and their applied meanings	
$R_r = L(T_S)/L(T_T)$	meaning
$R_r = 1.0$	Target Self-illumination or source at same temperature as target
$R_r = .667$	Urban Setting
$R_r = 0.5$	Open field, winter time setting under a clear sky
$R_r = 0.0$	Source \ll target (i.e., exhaust stack)

2.3 WHEN TEMPERATURE IS INFERRED EXACTLY

Equation 2 presented above is still cumbersome to study because of the term containing $(\partial L/\partial T)$. A simpler form of equation 2 to work with is one that contains error terms for emissivity and reflection only. Justification for dropping the second term in equation 2 comes from Technical Memo #1 of March 1988, where it was implied that the current method FSTC uses to infer temperature results in close approximations of surface temperature. The greatest error introduced was found to be the error in emissivity when a signature was being calculated from a different view angle and wavelength band than the one at which the original data were collected. Further analysis will be presented here.

From Appendix A, an equation describing ΔT , the error in inferred temperature, can be written as

$$\Delta T = L^{-1} \left[\left(\frac{1}{\hat{\epsilon}} \right) \{ \epsilon L(T_T) + (1 - \epsilon) L(T_S) \} \right] - T_T \quad (3)$$

where:

T_T = true target temperatures,

$\hat{\epsilon}$ = estimated emissivity,

ϵ = true emissivity,

T_S = reflection source temperature,

$L^{-1}()$ = temperature inferred from a given radiance,

where all of the above quantities pertain to the waveband/view geometry at which the target radiance was actually measured (cf., Appendix A).

For the present study, $\hat{\epsilon} = 0.95$, and since 0% error is desired, $\Delta T = 0$ as well. Then

$$T_T = L^{-1} \left[1.05 \left\{ \epsilon L(T_T) + (1 - \epsilon) L(T_S) \right\} \right] \quad (4)$$

Or, rewriting in terms of radiance

$$L(T_T) = 1.05 \left\{ \epsilon L(T_T) + (1 - \epsilon) L(T_S) \right\} \quad (5)$$

and then dividing by $L(T_T)$

$$1 = 1.05 \left\{ \epsilon + (1 - \epsilon) \frac{L(T_S)}{L(T_T)} \right\} \quad (6)$$

where, $L(T_S)/L(T_T) = R_r$, the reflectance ratio presented earlier. Choosing the same values of R_r , namely $R_r = 1, 0.5, 0.667$ and 0 , allows equation 6 to have a single variable, ϵ . Table 2 shows the emissivities that result in 0% error in inferred temperature when the emissivity is estimated to be 0.95 for the reflectance ratios chosen.

TABLE 2	
Emissivities that result in 0% error in inferred temperature vs Reflection ratio $R_r = L(T_S)/L(T_T)$	
R_r	ϵ
1	* impossible
.667	.85
.5	.9
0	.95

Table 2 shows that when the reflection source and target temperature are the same, no real emissivity combined with the assumed emissivity of 0.95, can result in 0% error, which makes intuitive sense. When the reflection source temperature is lower than the target temperature (as is usually the case), the actual target emissivity must be relatively high (>0.85) in order to have small errors in inferred temperature.

The importance of this analysis shows that the actual target emissivities must be relatively high for there to be 0% error in inferred temperature when a high estimated emissivity is used. Naturally, this is in direct opposition to the basic assumption of this report, i.e., that emissivity at some view angles may actually be low due to the specular nature of real world target surfaces. However, one must keep in mind that we are presently considering two different emissivities. One is the emissivity of the target at the waveband/geometry from which actual target radiance is measured. This is denoted ϵ_1 in Appendix A, and is the emissivity relevant to the error in inferred target temperature ΔT . The second emissivity, denoted ϵ_2 in the appendix, is at the waveband/geometry of the IR simulation. One may reasonably hypothesize a situation in which ϵ_1 is high (i.e., target radiance measured at near normal incidence) but ϵ_2 is low (e.g., simulation view angle near grazing). Indeed, the derivation of equation (1) assumed the error in inferred temperature was not large; this can only occur if ϵ_1 is reasonably high.

A given error in inferred temperature ΔT represents an essentially fixed amount of error in the simulated radiance. Thus, in order to parametrically exercise our error equation (2), we may fix the term involving ΔT to any desired level. For the sake of simplicity, we choose this level to be zero in the remainder of this report. This permits the impact of the remaining terms to be more easily understood.

2.4 THE REDUCED EQUATION TO BE STUDIED

With the dropping of the second term that describes the error due to error in inferred temperature, the equation describing error now becomes

$$\frac{\Delta L}{L(T_T)} = (\hat{\epsilon} - \epsilon) - (1 - \epsilon) R_r \quad (7)$$

Equation 7 will be used in the rest of this report in order to study error due to neglecting reflections and misestimating emissivity.

An important point about equation 3 is that if the estimated emissivity, $\hat{\epsilon}$, is greater than the true emissivity, ϵ , and close to 1, and the reflectance ratio is non-zero, the two terms in equation 3 tend to be compensating. That is, if

$$\hat{\epsilon} > \epsilon \quad \text{and} \quad \hat{\epsilon} \sim 1 \quad \text{and} \quad R_r \sim 1 \quad ,$$

then

$$(\hat{\epsilon} - \epsilon) - (1 - \epsilon) \sim 0 \quad .$$

This immediately ensures that error will be low as long as:

- 1) The reflection source is close to the temperature of the target ($R_r \sim 1$).
- 2) The dropped term concerning inferred temperature is indeed close to 0.

3.0 APPLYING THE ERROR EQUATION TO A REALISTIC TARGET

3.1 INTRODUCTION

In section 2, a means of studying error has been derived in equation form, equation 7. This section discusses exactly how to use it to gain insight into sources and magnitudes of error. This was partly accomplished in section 2.3 by selecting four values of reflectance ratio, R_r , in order to set limits based on the given underlying assumptions. The task discussed here is to further develop a means of achieving insight into the problem of reflected term error in realistic situations.

3.2 A PROCEDURE FOR LOOKING AT REALISTIC SITUATIONS

A realistic situation would be to apply the reduced form of equation 7 to an actual target and derive some meaningful statistics. One of the primary concerns at ERIM is that since some target surfaces can be highly specular, simulations of targets at some view angles could produce large amounts of error if reflections are not considered.

Calculating equation 7 using measurements from a foreign target would be the most direct means of studying the effects of neglecting reflectance error. Since radiance measurements of an actual tank would be costly, resort was made to using a computer simulation.

The GIFT code for describing and raytracing complicated targets was used for the simulation. A solid model of a T72 developed by BRL was "painted" with Mil-E-46096 olive drab paint. The paint's specular characteristics had previously been measured by ERIM [1]. The T72 was then raytraced, using the GIFT code, and histograms of emissivities were constructed for various azimuth and elevation angles. These histograms were then used to derive error statistics that lend insight into how much error could be expected and/or tolerated by applying the derived emissivities to equation 7. The histograms were constructed by grouping emissivities

computed through the raytrace into four categories. These categories are shown in Table 3.

TABLE 3	
Bins used for constructing Histogram	
Category	Emissivity Range (Bin Width)
1	1.0 - .875
2	.875 - .75
3	.75 - .25
4	.25 - 0

By themselves, histograms like Table 3 do not give direct insight into reflectance error, although knowledge of how many computed emissivities fall into categories 1 and 2, for example, may provide intuitive insight into the level of error present due to reflections. However, by applying equation 7 in a meaningful manner, one may derive direct error percentages.

One way of calculating meaningful error percentages is to assume a worst case analysis and apply equation 7 to each category in the histogram, then multiply the percentage of emissivities that fall into each category by the error derived for each. This results in a worst case weighted average error for the view angle that derived the histogram. In equation form, this error is

$$E_w = \sum_{i=1}^4 N_i * e_i \times 100 \quad (8)$$

where:

- N_i = decimal fraction of emissivities computed in category i ,
- e_i = error calculated using equation 7 and lowest emissivity in category i (e.g., 0.875 for category 1),
- E_w = worst case weighted average error for the view angle used to derive the N_i in percent (%).

Figure 3 summarizes the procedure used to calculate error curves.

3.3 THE ERROR CURVES DERIVED FROM THE PROCEDURE

Since looking at a broad spectrum of targets and view angles would be expensive, even using simulation, it was decided that a single target, the T72, and a limited set of histograms based on view angles around the target would be derived. These histograms were then used as the histogram N_i for equation 8 above. From this limited data set, sufficient insight is derived to draw further conclusions.

Three azimuths were chosen as being representative of typical engagement scenarios (which is the ultimate aim of the total simulation task). Two head-on azimuths and an off angle azimuth were selected as representative. Five elevations in all were selected. Three elevations at low grazing angles were selected since it was expected that the greatest error would be concentrated at these angles. High error was expected at these low grazing angles because, as mentioned earlier, the military paint simulated exhibits specular behavior at low grazing angles. Figure 4 shows the three azimuths studied and Figure 5 shows the five elevations studied. Tables 4, 5, and 6 show the worst case weighted average error computed for azimuth = 45° , 0° , and 180° , respectively, at the elevation angles listed and for the values of reflectance ratio, R_r , discussed in section 2.0.

Figure 6 graphs Tables 4, 5, and 6.

Appendix B shows the actual histograms of emissivities computed which created Tables 4 through 6.

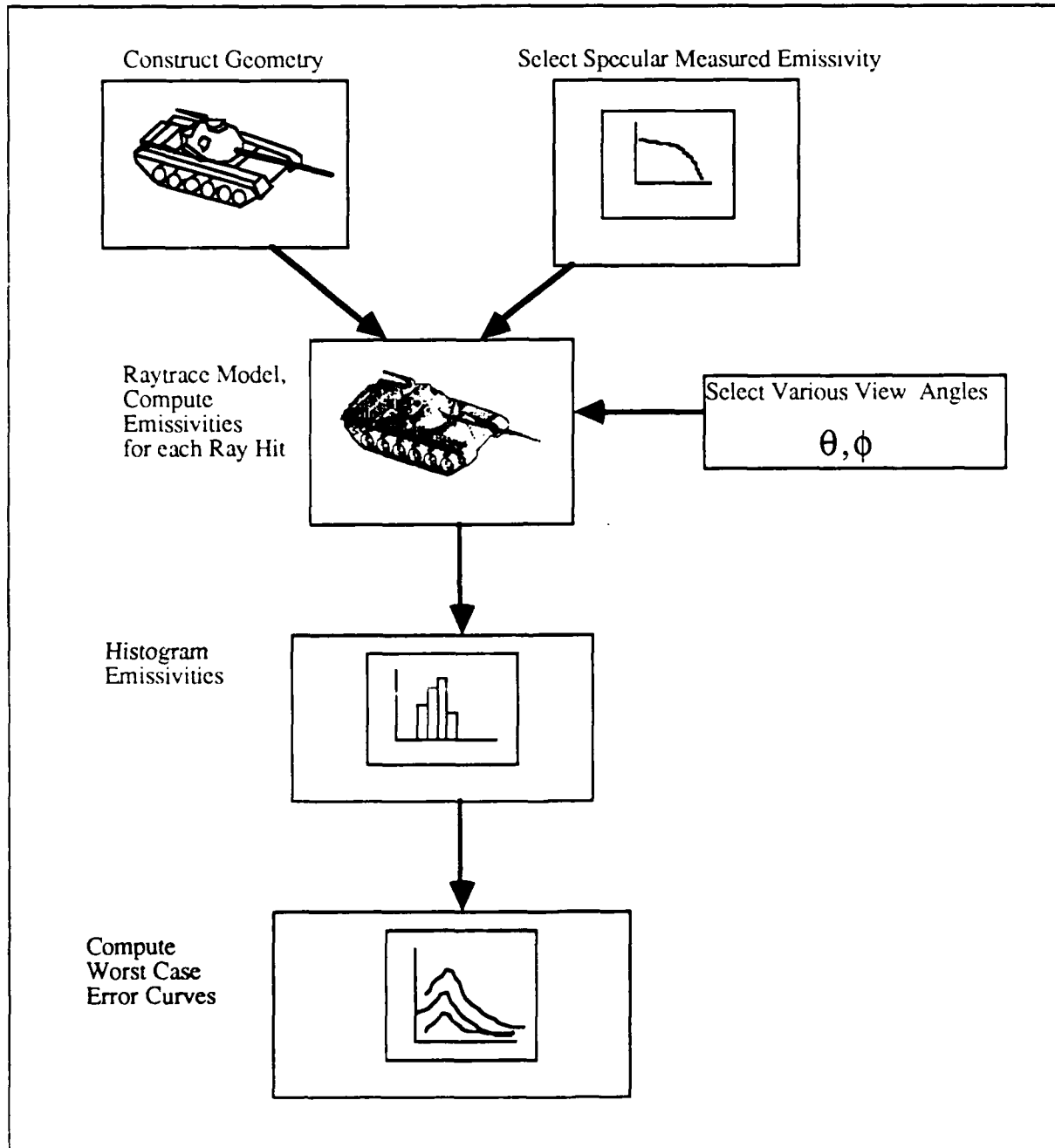


FIGURE 3. SUMMARY OF PROCEDURE USED TO CALCULATE WORST CASE ERROR CURVES.

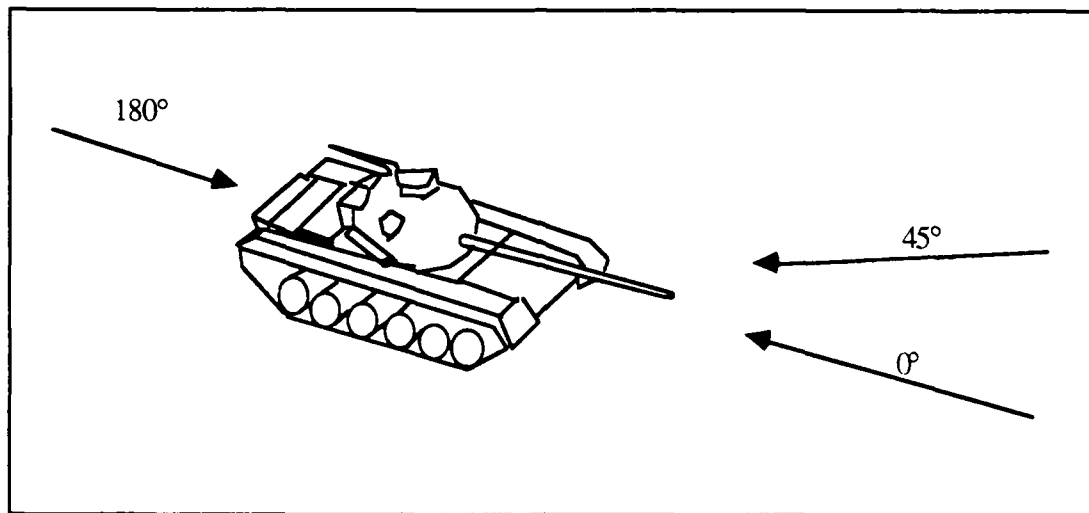


FIGURE 4. SELECTED AZIMUTH ANGLES.

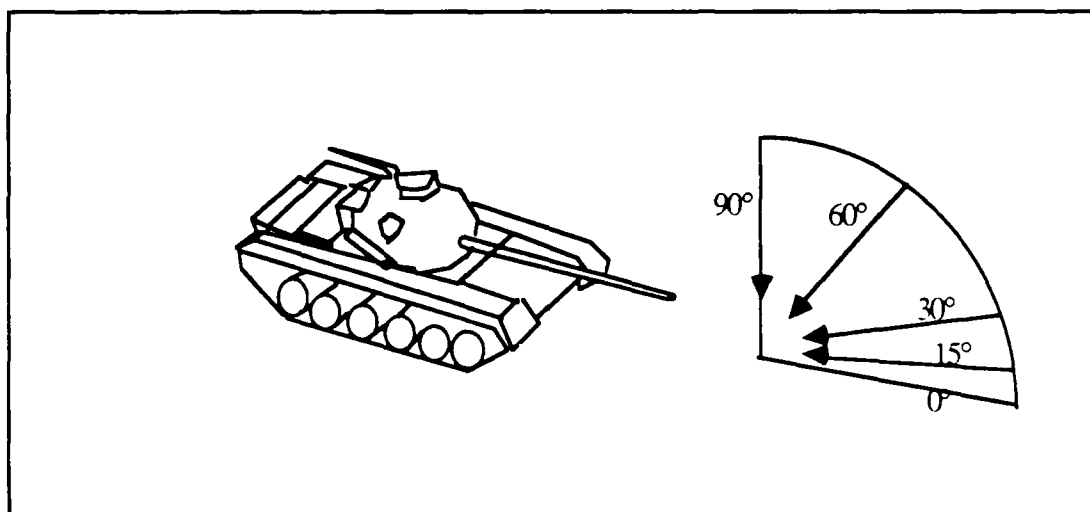
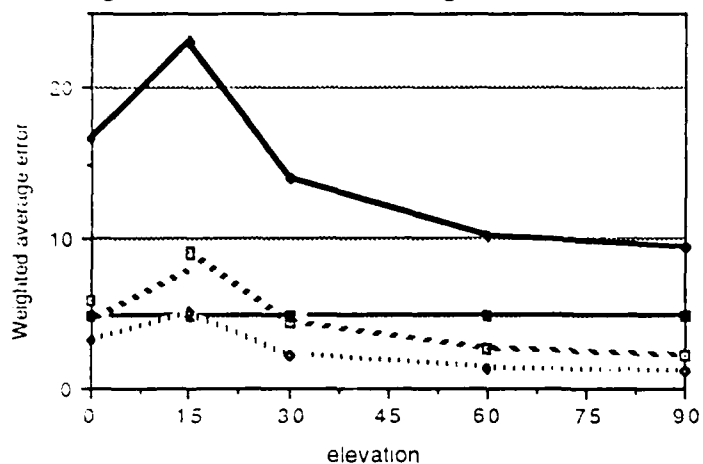
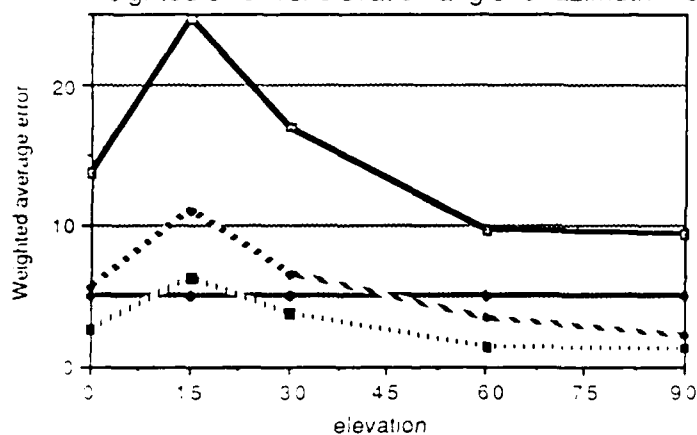


FIGURE 5. SELECTED ELEVATION ANGLES.

Weighted error vs. elevation angle for azimuth = 45.



Weighted error vs. elevation angle for azimuth = 0.



— Rr = 0.0
 - - - Rr = 0.5
 Rr = .667
 — Rr = 1.0

Weighted error vs. elevation angle for azimuth = 180

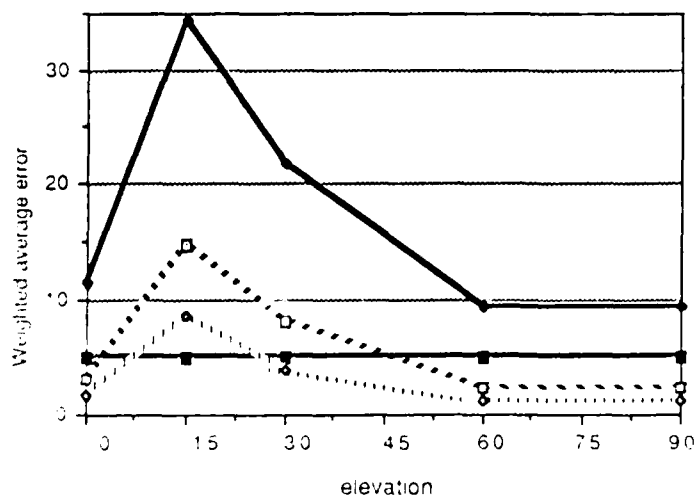


FIGURE 6. ERROR CURVES BASED ON WEIGHTED AVERAGE ERROR COMPUTED IN TABLES 4, 5, AND 6.

TABLE 4

Worst case weighted average Error, E_w , for Azimuth = 45°

Elevation	$R_r=1.0$	$R_r=.667$	$R_r=.5$	$R_r=0.0$
0.0	5.0	3.18	5.8	16.6
15.0	5.0	5.04	9.1	23.1
30.0	5.0	2.16	4.5	14.0
60.0	5.0	1.39	2.58	10.16
90.0	5.0	1.26	2.19	9.37

TABLE 5

Worst case weighted average Error, E_w , for Azimuth = 0.0

Elevation	$R_r=1.0$	$R_r=.667$	$R_r=.5$	$R_r=0.0$
0.0	5.0	2.66	5.5	13.77
15.0	5.0	6.19	11.0	24.7
30.0	5.0	3.75	6.5	16.9
60.0	5.0	1.315	3.4	9.6
90.0	5.0	1.26	2.19	9.37

TABLE 6

Worst case weighted average Error, E_w , for Azimuth = 180

Elevation	$R_r=1.0$	$R_r=.667$	$R_r=.5$	$R_r=0.0$
0.0	5.0	1.67	3.2	11.4
15.0	5.0	8.59	14.7	34.4
30.0	5.0	3.93	8.11	21.7
60.0	5.0	1.24	2.19	9.33
90.0	5.0	1.26	2.19	9.37

3.4 INTERPRETATION OF THE ERROR CALCULATED

The curves in Figure 6 establish a trend in error that is view angle dependent. The peak in error occurs at 15° elevation for all azimuth values and drops to its lowest value at 90° elevation. The reason for this elevation angle dependency is due to the specular behavior of the emissivity used.

Interpretation needs to be applied to the curves presented, since in all cases, there is error that peaks above 20% and in one case peaks at 35%. The largest error is caused by the curve computed for the relatively uncommon reflectance ratio, $R_r = 0.0$. The other reflectance ratios, 0.5, 0.667, and 1.0, are more representative of realistic scenarios. For these other cases, the error is mostly below 10%, and peaks at 15%. For elevation angles $> 45^\circ$, the computed error is less than 5%.

The curves in Figure 6 represent error bounds, since no actual vehicle would consist wholly of any one of the reflectance ratios chosen. In reality, the author speculates that an average reflectance ratio for a realistic situation would be somewhere between 0.667 and 1.0, based on the observation that many parts of a vehicle tend to be near air temperature.

In summary, the following points can be made:

- The highest error occurs for a reflectance ratio, $R_r = 0.0$, that occurs infrequently on a vehicle such as hot exhaust stacks and other very hot engine parts.
- Low error was calculated for scenarios that might be typical of steep elevation angles.
- Excluding the reflectance case of $R_r = 0.0$, most errors computed were less than 10%, which are on the order of 6°K apparent temperature at 300°K.

4.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

As stated in section 1.0, the purpose of this study is to determine whether it is necessary to model reflections in the current FSTC method of simulating IR signatures. To gain more insight the following steps were performed:

- 1) A sensitivity analysis approach was chosen for the study.
- 2) An equation isolating the major components of an IR signature was derived.
- 3) The equation was used to determine error present in a simulation when emissivity was estimated to be always 0.95. This was accomplished by using a simulation of a complicated tank applied with actual, measured emissivity that had specular characteristics.
- 4) A weighted average error figure was derived and applied to the results of histogramming emissivities for the simulated tank.
- 5) It was determined that in some cases, error could be as high as 35% on an absolute scale. However, most of the errors calculated in section 3.0 were found to be less than 10%.

Conclusions

- It was stated in Technical Memo #1 that temperature is inferred correctly in most of the situations that FSTC will collect data. However, the analysis presented in section 2.3 contradicts this inference. Therefore, further study using an approach similar to the one presented must be performed for determining error in inferred temperature. Unfortunately, the question of including or not including the effects of reflections when inferring temperatures from collected data remains unclear.

- It was shown in section 2.4 that both mis-estimating emissivity at a high value (~ 0.95) and neglecting reflections results in compensating errors, if the reflectance ratio, R_r is ~ 1.0 . This interpretation is

shown clearly in Figure 6 by the fact that the greatest error is computed for the curve when $R_r = 0$.

Discussion

It is inappropriate at this stage for ERIM to make value judgments concerning the error in FSTC's current simulation method, since ERIM is unaware intimately of the needs and uses of FSTC's simulation product. However, it can be stated that a 10% error is equivalent to about a 6°K apparent temperature error [3]. The question of whether this is important or not depends on the sensitivity of the IR systems being designed using FSTC's simulation products. Another key issue is the fact that most IR seeker systems are AC-coupled devices that measure the contrast between a target and the background. The analysis presented in this study ignores this consideration.

It is possible to talk in general terms about the sensitivity of IR seeker systems evaluated by ERIM in the past, as in reference [2]. Methods have been used to evaluate IR system performance, usually defining a probability of detection or lock-on of a seeker system given range and target-to-background signal contrast. In some cases, small changes in temperature contrast can result in large differences in projected detection ranges.

Figure 7 shows curves relating lock-on probability to range at three fixed temperature contrasts for the Maverick seeker [2]. It is striking to the authors the difference in these curves given a single degree of change in temperature contrast. If judgments are made concerning IR systems with this level of sensitivity using data that is 6° in error, the judgments may be wrong. If, on the other hand, a typical seeker has a dynamic range of 200°K , 6° of error may not affect judgment at all.

Recommendations

Following is a list of recommendations that are based on the conclusions of this report:

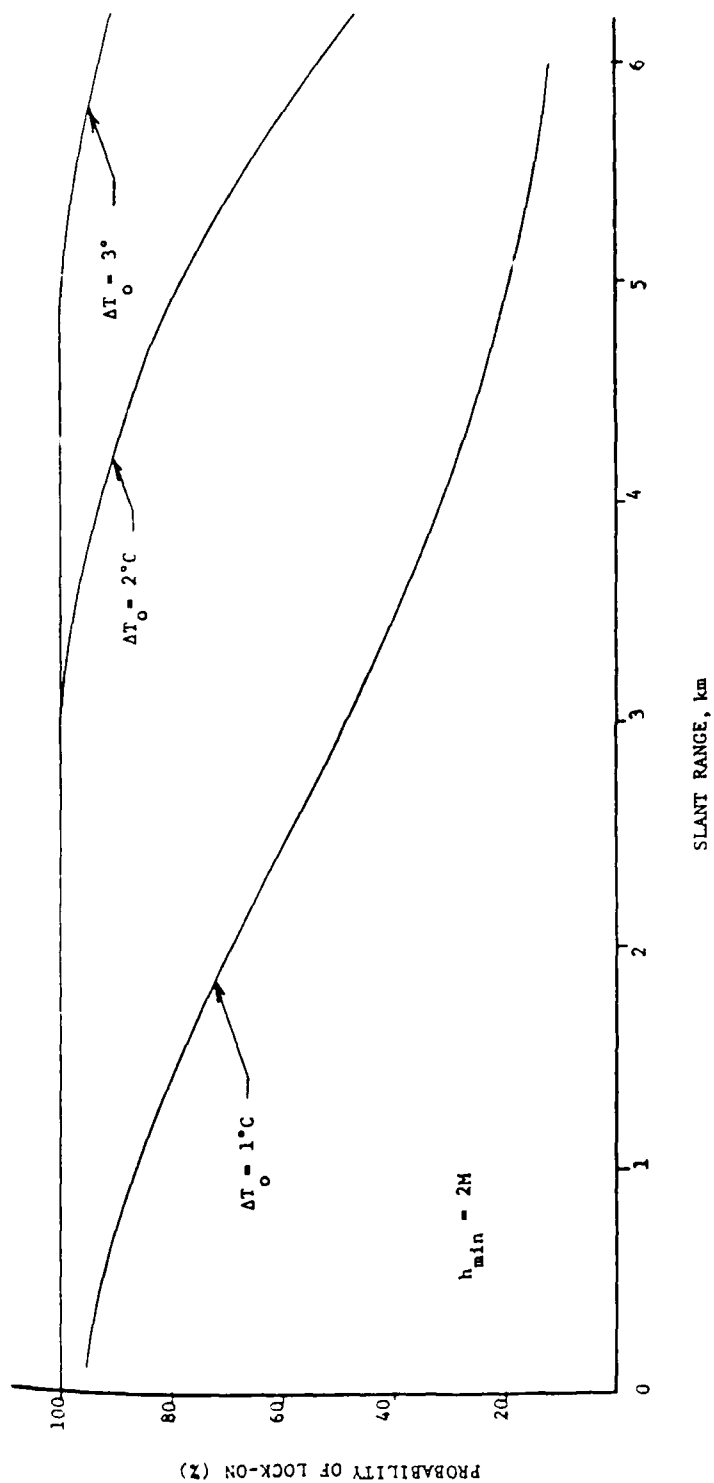


FIGURE 7. LOCK-ON PROBABILITY FOR 1-, 2-, AND 3°C TARGETS FOR MAVERICK SEEKER.

- The sensitivity of error due to incorrectly inferring temperature needs to be studied in more depth. A procedure similar to the one used in this report should be used, as the case study method used before is too limiting.
- A decision by FSTC personnel needs to be made concerning whether the errors reported in section 3 are significant to their customers.
- Based on the decision above, corrective action can be planned for by ERIM and FSTC (i.e., including reflections and specular emissivity in TOTSIG).

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- [3] J. Beard, Personal Communication.
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APPENDIX A
DERIVATION OF ERROR EQUATION

A.1 INTRODUCTION

In this appendix we derive equation (1) of section 2.0, which specifies the total error in a simulated target radiance. (Note: When we speak of the radiance or temperature of "the target," we are actually referring to some target component or facet having uniform thermodynamic and optical properties.) The derivation is based on a number of assumptions regarding how the radiance simulation is performed. Specifically, the simulation is assumed to consist of the following three steps:

- Step 1. The actual target radiance in some wavelength band, $\Delta\lambda_1$, is measured by a calibrated radiometer (e.g., a calibrated FLIR) at some view angle θ_1 ;
- Step 2. Based on the radiance measured in Step 1, an actual (i.e., thermodynamic) target temperature is calculated;
- Step 3. The temperature from Step 2 is then used in a radiometric model to predict target radiance at some other view angle θ_2 , and/or within some other wavelength band $\Delta\lambda_2$.

A.2 DEFINITIONS AND NOTATIONS

- Planck spectral radiance from a blackbody, $L_{BB}(\lambda, T)$:

$$L_{BB}(\lambda, T) = \frac{C_1}{\lambda^5} \frac{1}{\left[e^{C_2/\lambda T} - 1 \right]} \quad (A-1)$$

C_1, C_2 = constants,
 λ = wavelength,
 T = temperature.

- In-band radiance within wavelength band $\Delta\lambda_i$, $L_i(T)$:

$$L_i(T) = \int_{\Delta\lambda_i} L_{BB}(\lambda, T) d\lambda \quad . \quad (A-2)$$

- Differential in-band radiance w.r.t. temperature, $\left. \frac{\partial L_i}{\partial T} \right|_T$

$$\left. \frac{\partial L_i}{\partial T} \right|_T = \int_{\Delta\lambda_i} \frac{\partial}{\partial T} L_{BB}(\lambda, T) d\lambda \quad . \quad (A-3)$$

(Note: Equations (A-2) and (A-3) are typically evaluated numerically, as are many of the equations given below.)

- In-band directional emissivity, $\epsilon_i(\theta, T)$

$$\epsilon_i(\theta, T) = \frac{\int_{\Delta\lambda_i} \epsilon(\lambda, \theta, T) L_{BB}(\lambda, T) d\lambda}{\int_{\Delta\lambda_i} L_{BB}(\lambda, T) d\lambda} \quad (A-4)$$

$\epsilon(\lambda, \theta, T)$ = spectral, directional emissivity at temperature T ,
 θ = abbreviated notation for view direction (θ, ϕ) .

- Bi-directional reflectance distribution function (BRDF), $\rho'(\theta_r, \phi_r; \theta_i, \phi_i)$:

$$\rho'(\theta_r, \phi_r; \theta_i, \phi_i) = \frac{L(\theta_r, \phi_r)}{E(\theta_i, \phi_i)} \quad , \quad (A-5)$$

$E(\theta_i, \phi_i)$ = irradiance incident from direction θ_i, ϕ_i (cf., Figure A-1),

$L(\theta_r, \phi_r)$ = radiance reflected into direction θ_r, ϕ_r (Figure A-1).

Note that for opaque surfaces,

$$\epsilon(\theta, \lambda) = 1 - \iint \rho'(\theta_r, \phi_r; \theta_i, \phi_i) \cos \theta_r d\theta_r d\phi_r \quad . \quad (A-6)$$

Here, $\epsilon(\theta, \lambda)$ is the directional emissivity in the direction (θ_i, ϕ_i) .

- Reflection term into view direction θ , $RT(\theta)$:

- General surface

$$RT(\theta) = \iint \rho'(\theta_r, \phi_r; \theta_i, \phi_i) L[T_s(\theta_i, \phi_i)] \cos \theta_i d\theta_i d\phi_i \quad (A-7a)$$

$T_s(\theta_i, \phi_i)$ = hemispherical distribution of apparent temperature (e.g., sky temperature).

- Perfectly specular surface

$$RT(\theta) = \Gamma(\theta) L[T_s(\theta, \phi_r - 180^\circ)] \quad (A-7b)$$

$\Gamma(\theta)$ = Fresnel reflectivity,

$T_s(\theta, \phi_r - 180^\circ)$ = apparent temperature at the specular geometry:

$$\theta_i = \theta_r; \phi_i = \phi_r - 180^\circ.$$

- Perfectly diffuse surface

$$RT = \frac{\rho}{\pi} \iint L[T_s(\theta_i, \phi_i)] \cos \theta_i d\theta_i d\phi_i \quad (A-7c)$$

$$= \frac{\rho}{\pi} E_{\text{down}} \quad ,$$

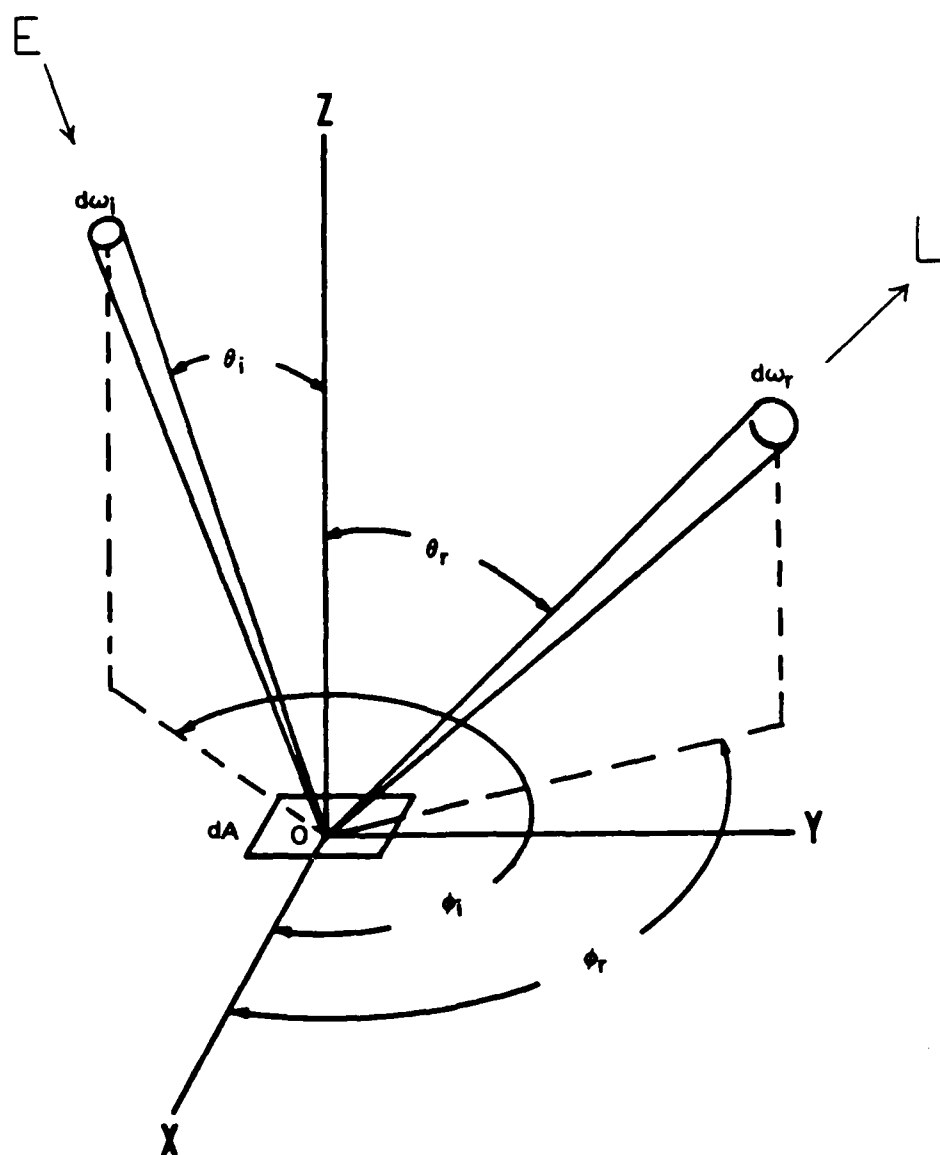


FIGURE A-1. BRDF GEOMETRY (ADAPTED FROM REF. [4]).

ρ = hemispherical reflectivity,
 E_{down} = total downwelling irradiance.

Note the lack of any θ -dependence for the diffuse case.

- Relation between actual and apparent temperature

$$L_i(T^{\text{app}}(\theta)) = \epsilon(\theta) L_i(T^{\text{act}}) + RT_i(\theta) \quad (\text{A-8})$$

$T^{\text{app}}(\theta)$ = target apparent temperature when viewed at angle θ .

Note that in equation (A-8) we have not shown any temperature dependence for emissivity. Although equation (A-4) shows that this is not strictly valid, it is usually a good approximation over temperature ranges of a few tens of degrees Celsius. This is indeed fortunate when temperature is the unknown to be determined.

A.3 DERIVATION OF EQUATION (1)

Armed with the definitions of the previous section, we may now readily derive the equation for error in simulated radiance. The derivation consists simply of writing equations that describe the three steps of the simulation procedure listed in section A.1.

Step 1. Measurement of Target Radiance

For a radiometer having a spectral passband $\Delta\lambda_1$ and view direction θ_1 , the measured radiance from the target is

$$L_1(T^{\text{app}}(\theta_1)) = \epsilon_1(\theta_1) L_1(T^{\text{act}}) + RT_1(\theta_1) \quad (\text{A-9})$$

Step 2. Estimation of Actual Target Temperature

FSTC's present method of temperature estimation is based on two assumptions: 1) the reflected component of the measured target radiance is negligible (i.e., $RT_1(\theta_1) = 0$); 2) the target emissivity is assumed to

be angularly-independent and have a constant value of 0.95 in the LWIR and 0.6 in the MWIR. We shall generalize the second assumption by writing

$$\epsilon_1(\theta_1) = \hat{\epsilon}_1 \quad .$$

With these two assumptions, the estimate of actual temperature, \hat{T} , may then be written from equation (A-9) as

$$\hat{T} = L_1^{-1} \left[\frac{1}{\hat{\epsilon}_1} L_1(T^{\text{app}}(\theta_1)) \right] \quad (\text{A-10})$$

where $L^{-1}(\)$ denotes an inversion of the band radiance versus temperature function defined in equation (A-2).

We may express this temperature estimate as the sum of the true target temperature and some temperature error, ΔT , i.e.,

$$\hat{T} = T^{\text{act}} + \Delta T \quad . \quad (\text{A-11})$$

Note in equation (A-10), that T , and therefore ΔT , depends on the view direction θ_1 .

Step 3. Radiance Simulation

The estimated target temperature \hat{T} is used to calculate target radiance at some other view angle and/or some other wavelength region. In the general case, both differences may apply; we therefore denote the simulated radiance as $\hat{L}_2(\theta_2)$. If we again employ the FSTC radiance model, i.e., ignore any reflected component in the new wavelength region, we may write

$$\begin{aligned}\hat{L}_2(\theta_2) &= \hat{\epsilon}_2 L_2(\hat{T}) \\ &= \hat{\epsilon}_2 L_2(T^{\text{act}} + \Delta T) \quad .\end{aligned}\tag{A-12}$$

In equation (A-12) $\hat{\epsilon}_2$ is the estimate of target emissivity in the simulated waveband/view direction.

The correct value of target radiance is given by the following

$$L_2(\theta_2) = \epsilon_2(\theta_2) L_2(T^{\text{act}}) + RT_2(\theta_2) \quad .\tag{A-13}$$

The error in simulated radiance, ΔL_2 , is the difference between (A-12) and (A-13), i.e.,

$$\begin{aligned}\Delta L_2 &= \hat{L}_2(\theta_2) - L_2(\theta_2) \\ &= \hat{\epsilon}_2 L_2(T^{\text{act}} + \Delta T) - L_2(\theta_2) \quad .\end{aligned}\tag{A-14}$$

If ΔT is not too large, we may approximate $L_2(T^{\text{act}} + \Delta T)$ by the first two terms of a Taylor series expansion around T^{act} , i.e.,

$$L_2(T^{\text{act}} + \Delta T) \approx L_2(T^{\text{act}}) + \left. \frac{\partial L_2}{\partial T} \right|_{T^{\text{act}}} (\Delta T) \quad .\tag{A-15}$$

Inserting equations (A-15) and (A-13) into (A-14) we obtain

$$\Delta L_2 = [\hat{\epsilon}_2 - \epsilon_2(\theta_2)] L_2(T^{\text{act}}) + \hat{\epsilon}_2 \frac{\partial L_2}{\partial T} \Delta T - RT_2(\theta_2) \quad .$$

If we consider the special case of an opaque specular surface, the reflection term $RT_2(\theta_2)$ may be replaced by $(1 - \epsilon_2(\theta)) L_2(T_s(\theta_2))$, as in equation (A-7b). (Note that for an opaque surface the reflectivity is one minus the emissivity.) Making this replacement in the above equation, we obtain our final result,

$$\Delta L = (\hat{\epsilon} - \epsilon) L(T^{\text{act}}) + \hat{\epsilon} \frac{\partial L}{\partial T} \Delta T - (1 -) L(T_s) \quad . \quad (\text{A-16})$$

Equation (A-16) is identical with equation (1) of section 2.0. The subscripts and references to θ_2 have been dropped as it is understood that all quantities in (A-16) are defined for the simulated wavelength region and view direction. The only exception is the quantity ΔT , which is independent of the simulation. Using equations (A-9), (A-10), and (A-11), we write the following equation for the error in estimated target temperature:

$$\begin{aligned} \Delta T &= \hat{T} - T^{\text{act}} \\ &= L_1^{-1} \left\{ \left[\frac{1}{\hat{\epsilon}_1} \right] \left[\epsilon_1(\theta) L_1(T^{\text{act}}) + RT_1(\theta_1) \right] \right\} - T^{\text{act}} \quad . \quad (\text{A-17}) \end{aligned}$$

As shown above, ΔT depends only on quantities defined for the waveband/view direction from which the target radiance was actually measured.

APPENDIX B

EMISSIONIVITY HISTOGRAMS

B.1 INTRODUCTION

In order to compute the weighted average errors displayed in Tables 4 through 6, histograms of emissivities, had to be constructed. This was done using the procedure outlined in section 3.0. This Appendix lists the actual histograms derived for the various view angles considered.

B.2 COMPUTED HISTOGRAMS

Following Table 3 in section 3.0, histograms of emissivities were computed. The following tables, B.1, B.2, and B.3, show the computed histograms for the azimuth and elevation angles listed.

TABLE B.1				
HISTOGRAM FOR AZIMUTH = 0.0				
Elevation Angle	Emissivity Bins			
	0-0.25	0.25-0.75	0.75-0.875	0.875-1.0
0	0.018	0.020	0.460	0.490
15	0.048	0.188	0.300	0.450
30	0.020	0.040	0.510	0.410
60	0.004	0.012	0.090	0.880
90	0.006	0.008	0.070	0.913

TABLE B.2				
HISTOGRAM FOR AZIMUTH = 45°				
Elevation Angle	Emissivity Bins			
	0-0.25	0.25-0.75	0.75-0.875	0.875-1.0
0	0.021	0.073	0.216	0.689
15	0.028	0.160	0.260	0.541
30	0.008	0.015	0.400	0.570
60	0.005	0.009	0.134	0.850
90	0.006	0.008	0.070	0.913

TABLE B.3				
HISTOGRAM FOR AZIMUTH = 180°				
Elevation Angle	Emissivity Bins			
	0-0.25	0.25-0.75	0.75-0.875	0.875-1.0
0	0.003	0.020	0.200	0.768
15	0.070	0.306	0.141	0.470
30	0.030	0.050	0.640	0.270
60	0.004	0.009	0.080	0.896
90	0.006	0.008	0.070	0.913

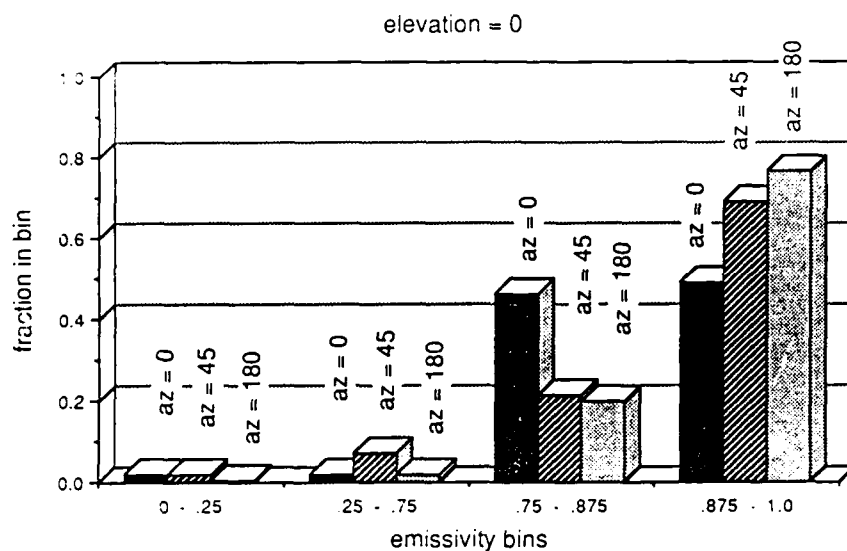


FIGURE B-1. HISTOGRAM FOR EMISSIVITIES CALCULATED AT ELEVATION ANGLE = 0 AND ALL THREE AZIMUTH ANGLES.

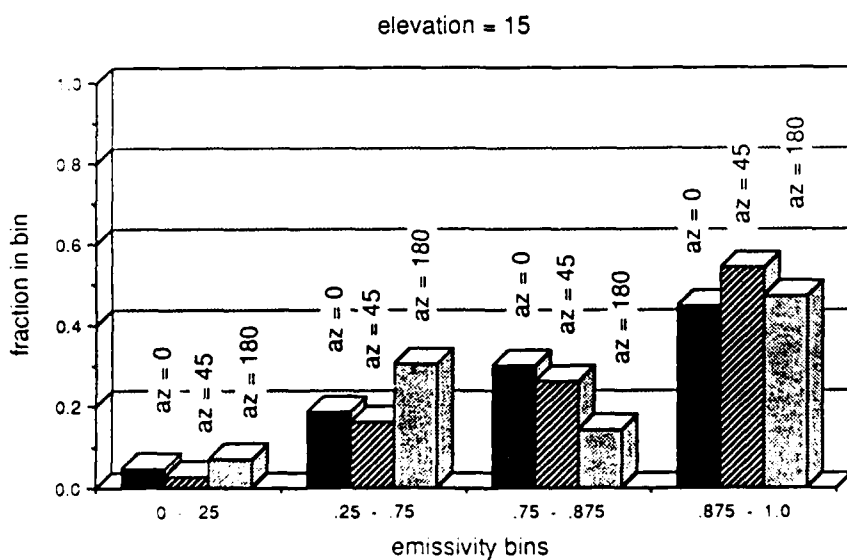


FIGURE B-2. HISTOGRAM FOR EMISSIVITIES CALCULATED AT ELEVATION ANGLE = 15 AND ALL THREE AZIMUTH ANGLES.

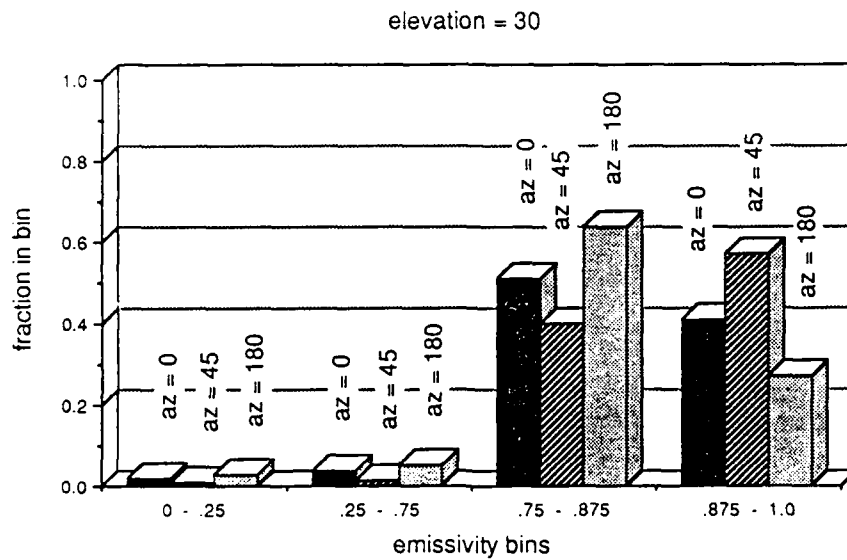


FIGURE B-3. HISTOGRAM FOR EMISSIVITIES CALCULATED AT ELEVATION ANGLE = 30 AND ALL THREE AZIMUTH ANGLES.

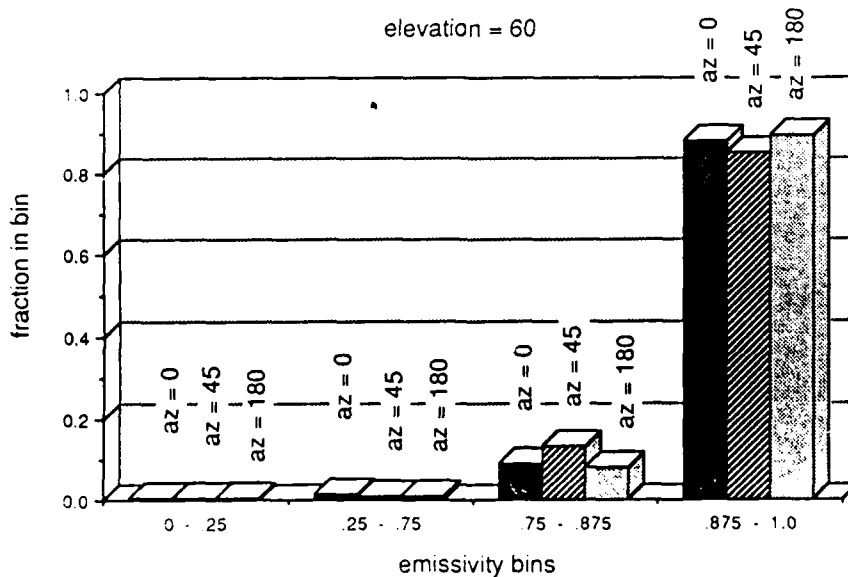


FIGURE B-4. HISTOGRAM FOR EMISSIVITIES CALCULATED AT ELEVATION ANGLE = 60 AND ALL THREE AZIMUTH ANGLES.

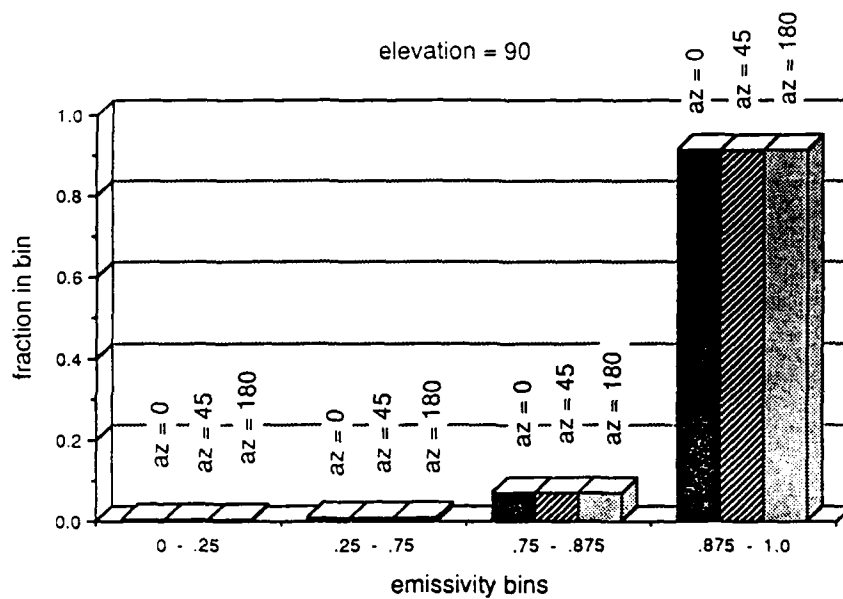


FIGURE B-5. HISTOGRAM FOR EMISSIVITIES CALCULATED AT ELEVATION ANGLE = 90 AND ALL THREE AZIMUTH ANGLES.